



in so doing, create even more projectiles and therefore more collisions. The 2013 movie Gravity (starring Sandra Bullock and George Clooney) portrayed this crisis, known as the Kessler effect after the NASA scientist who first proposed it, as a single runaway event. But in real life, it probably wouldn't happen all at once. Instead, over the years, the rate of satellite destruction and shrapnel production would increase collisions every ten years, every five, every two—until low earth orbit becomes effectively unusable for the better part of a century. And short of the full-blown destruction of everything in low earth orbit, an "economic Kessler effect" could prohibit the investment necessary to

photons of light, which carry about a billionth of the energy of a mosquito in flight. Perhaps, by extension, human vision might directly perceive purely quantum phenomena, such as a superposition in which the photon is in two places at the same time. Tantalizing research from Holmes and others is beginning to suggest that at least the former may be true, even though singlephoton detection as a technology, while well established, remains quite specialized.

"The rod cells of the human eye are single-photon detectors," says Holmes. "It's just a question of whether or not the signal makes it all the way to the conscious mind, rather than getting lost or discarded as noise."

Looking directly at the sun (not recommended) would allow the eye to take in a few thousand trillion photons per second. Yet human eyesight can possibly detect a single photon and can definitely detect a few. And if such extremely low-power optical signals can trigger a human eye that's optimized for signals

## TO REGISTER AN INCREDIBLY FAINT SIGNAL

# FROM A TINY, SELF-POWERED, MULTIDIRECTIONAL TRANSMITTER: TOO PIE IN THE SKY?

build and launch a satellite because its expected lifetime amidst the orbital debris is too brief.

Currently, the U.S. Air Force conducts extensive satellite tracking and can often arrange for one object to adjust its trajectory to avoid a potential collision. But to enact such a solution requires that both objects have been located and that at least one of them is capable of receiving instructions, equipped with a means of propulsion, and identifiable, so that the satellite's operator can be contacted and instructed to make the course adjustment-hopefully with sufficient lead time. Otherwise, there's no seeing the approaching brake lights, slowing down, or changing lanes. There are no space traffic jams. Only collisions.

### **Quantum vision**

Two years ago, before joining a Los Alamos team working to ease the satellite overcrowding problem, Rebecca Holmes was still in graduate school. There, studying quantum optics and collaborating with a Nobel prizewinner, she researched a hypothesis that is tantamount to heresy in conventional physics circles: that the human visual system might be able to see individual

exceeding trillions of photons per second, then what might be possible with a high-end photon detector optimized for extreme low-light conditions? Just how little energy could be put into a signal say, sent from a satellite to a ground station—so that it can still be seen?

### Signal science

From his office in the Laboratory's Nonproliferation and International Security Center, David Palmer pursues a technological solution to the orbitalovercrowding problem: something akin to air-traffic control, but for space traffic. Ideally, every space vehicle, whether currently in use or previously decommissioned—and for that matter every scrap of space junk—would be identifiable, controllable, and in constant communication with a central traffic-control ground station. This is not currently the case. To make it so, every new satellite launched would need to be equipped with some kind of transmission capability allocated to space-traffic control.

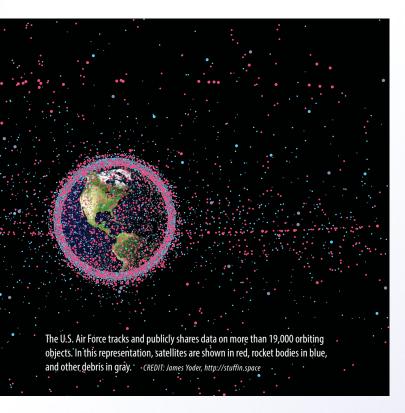


"That's already a sticking point," Palmer says. "Adding to a satellite's mass, power consumption, or functionality—and a radio antenna, for example, adds all three—always means increasing cost. But the cost needs to be negligible so that every government, every space research organization, and every telecom company

will participate, down to the universities, colleges, and even high schools now putting up their own CubeSats." The idea is that, over time, satellites with traffic-control functionality will replace what's up there now. But to catch on, the system would not only need to be cheap, but also tiny, self-sufficient, and completely trouble-free.

For a satellite, that's a tall order. Nominally, it would seem to require adding a dedicated radio antenna or partially repurposing an existing one. A dish-style antenna uses little power for transmitting but must be actively pointed toward the receiver, either by turning the dish or the whole spacecraft. That often means stopping whatever else the satellite is doing and consuming either power or propellant to make the turn. Alternatively, a rod-style antenna broadcasts in all directions and therefore need not be pointed, but it requires significant power because the signal must go out in every direction with enough strength to be picked up clearly in any one of them. Either solution is likely to be too resource-intensive for a traffic-management function that's not directly related to the satellite's intended purpose. What's needed is the best of both worlds: no pointing and no appreciable power consumption.

Palmer's solution is almost too pie in the sky to be believed: an incredibly faint optical broadcast from a tiny, self-powered transmitter that doesn't need to be pointed. Rather, it transmits in an enormous 120-degree cone, wide enough that the beam is likely to hit a ground receiver during a pass overhead, assuming that it's mounted on the Earth-facing side of the satellite.



The signal is composed of tremendously spread-out red laser light that can, nonetheless, be detected by a sensitive enough single-photon detector attached to a telescope, pointed at the satellite. Palmer's colleague David Thompson and his team have developed what turns out to be the perfect detector for this purpose—a phenomenally sensitive single-photon imaging



CubeSats, introduced in 1999, are responsible for much of the rapid proliferation of objects in low earth orbit. As of early 2019, more than a thousand have been launched, exceeding the rate of non-CubeSat launches in recent years. They typically use commercial off-theshelf components, have a mass of up to 1.33 kilograms (2.9 pounds), and occupy a frame 10 centimeters (4 inches) on a side, although this Los Alamos CubeSat, when folded up rather than deployed as shown, is  $10 \times 10 \times 15$  cm. PHOTO CREDIT: Michael Pierce

camera. And that camera, or even a lesser system based on singlephoton sensing without full-blown imaging capability, can pick up an ultrafaint, ultralow power optical transmission from a satellite if it is taught what to look for.

In theory, this should work. Still, much remains to be done to bring it from concept to testing to practical reality. So Palmer recruited Holmes, the unconventional single-photon sensing expert, to Los Alamos-and to the cause of rescuing low earth orbit.

### Hay in a haystack

What does it feel like to see just a few photons with your eye? "You are rarely sure you saw anything," says Holmes. "In the clearest trials, you might perceive a slight motion or a tiny suggestion of a flash." Confounding such an inherently inconclusive perception, any number of thermal noise processes or even outright hallucinations—could produce a false detection. And with any other light in the room at all, the signal would be completely drowned out.

These difficulties largely mimic the challenge of using an electronic single-photon ground detector to pick up a satellite's ultrafaint optical signal. The transmitter, which the team has dubbed the Extremely Low Resource Optical Identifier, or ELROI, will be roughly the size of a Scrabble tile, including its own dedicated solar cell. It won't "know" when or from where it is being tracked, so it will broadcast essentially continuously across the face of the earth. Matching the solar cell's available power to the power consumed by the transmission sets the signal strength: very, very low.

Even on a dark, moonless night, sunlight reflected by the satellite itself will easily overwhelm ELROI's signal. After putting a very restrictive filter on the detector scope to eliminate 99 percent of the incoming sunlight—all but a narrow range spanning the transmitted wavelength (that is, the exact shade of red)—photons of the correct wavelength in the reflected sunlight will still



The European Space Agency's Envisat performed an Earth-observing mission between 2002 and 2012. when contact was lost. At more than 8 tons, it is the most massive inactive satellite. It orbits at a particularly crowded altitude and regularly passes within a few hundred meters of other known satellites. A collision involving Envisat, even with a small piece of space debris, could dramatically accelerate a chain reaction of collisions in low earth orbit. PHOTO CREDIT: ESA

outnumber signal photons by about 90 to one. And simply detecting an excess is not good enough; the transmission would need to convey unambiguous information on the identity of the satellite, similar to a license plate on a car. To do that, the receiving system would have to somehow figure out which photons are likely to be signal photons and which are not.

This is a classic problem, separating signal from background or noise. For example, how might a researcher determine whether a human test subject really saw a single photon of light? Holmes sometimes envisions returning to this line of investigation at some point, after she has done her part to save the skies. First, she would have to repeat

imply that subjects were seeing single photons, at least sometimes. Only then, from a standpoint of understanding the rate at which single photons are perceived (if they are perceived at all), could she begin to examine the deeper question of whether human beings can perceive attributes of the photons' quantum states.

A satellite-signal receiver would also require the statistical analysis of many, many cycles of the same transmitted data string, from which to derive a basis for identifying certain flashes as containing a signal, not just background light. But unlike the human test subject, the satellite signal receiver would have to read the transmitted data reliably, not just determine whether it was on the left or the right. So it would need some additional way to differentiate signal photons from sunlight and other noise—something more than just statistical repetition.

### **Microsecond magic**

When the first pulsar was discovered—
a pulsing astronomical radio source with a pulse
rate more precise than an atomic clock—its

discoverer reportedly mistook it for a possible sign of alien technology. Pulsars were quickly identified with rapidly spinning neutron stars, which produce a flash with each rotation, like a lighthouse, but nonetheless, their tremendous regularity provides a model for separating the artificial from the natural. A manmade signal delivered with a precise, specific timing can be distinguished from the continuous background blur of sunlight, moonlight, starlight, and other forms of optical noise.

ELROI has been designed to transmit a satellite-identification number in 128 bits of data at a frequency of one kilohertz. That is, it either sends a flash or doesn't—a one or a zero—every thousandth of a second. After 128 thousandths of a second, or 128 milliseconds, the full identification number is complete and begins again, transmitting the full satellite ID almost eight times per second. That's the repetition; that's how the necessary detection statistics are obtained. The ground station will typically track the satellite across the sky for several minutes, so it will

receive the same 128-bit sequence hundreds or even thousands of times in a given orbit.

Each bit, or flash of light, lasts only a millionth of a second, which is a thousandth of a millisecond. So each millisecond begins with a microsecond flash (or not), followed by 999 microseconds of nothing. That makes two critical aspects of ELROI possible. It cuts power consumption by a factor

of a thousand, since it's only transmitting for one microsecond every millisecond. And it creates a very specific timing for the data photons: They arrive only in a specific microsecond at the beginning of every millisecond, like clockwork. The ground receiver can therefore ignore all the photons that arrive during the other 999 microseconds.

# DETECT A SINGLE PHOTON AND CAN DEFINITELY DETECT A FEW

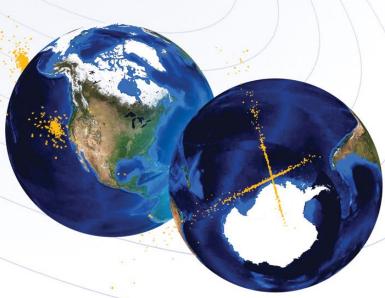
the experiment many, many times, with photons presented randomly on either the left or right side of the eye, to obtain statistics on how often a test subject could choose the correct side. Accuracy above guessing randomly, or 50 percent, would

In practice, isolating the photons that arrive with the proper timing is done with a "fast-folding algorithm" (the same algorithm used in modern pulsar searches) to identify the cyclical pattern. On occasion, some photons of sunlight of the right color will just happen to arrive during the proper microsecond, but they will be few enough that they can be rejected statistically, after many iterations of the complete 128-millisecond transmission. In other words, the extreme faintness of the signal relative to its background, even within the narrow wavelength band used, can be overcome by timing and repetition.

For instance, if the satellite ID were a six-digit number like most automobile license plates, then after filtering by wavelength and applying the fast-folding algorithm, such a transmission might be received several hundred times as "XYZ123," twice as "XYH123," and once as "XYZ193," making it easy to determine

# PRECISE TIMING HELPS SEPARATE A FAINT MANMADE SIGNAL FROM ITS NATURAL BACKGROUND

the real ID. In fact, in a two-minute segment of a satellite passing overhead, the ELROI system, using state-of-the-art error-correcting codes, has less than a one-in-a-billion chance of misidentifying a satellite ID. And even if an ID number were to be misread, the mistake would be discovered instantly because the vast majority of 128-bit numbers will not have a satellite assigned to them—unless humanity launches 2128 more satellites.



More than 2000 new pieces of debris were tracked (and, presumably, many more remain untracked) in the wake of a 2009 collision between two satellites: (left) twenty minutes after the collision and (right) 50 minutes after the collision.

CREDIT: Rlandmann/Wikipedia; data based on work of Astronautics Research Group, University of Southampton

### A little vision

At Los Alamos, experiments are in the works to observe the faint test beams from orbit with Thompson's single-photon imaging camera. For the test phase especially, the camera's imaging capability is a major bonus, easing the tracking requirements by allowing a satellite to be off-center within the telescope's field of view. However, commercially available singlephoton detectors can also read the satellite ID transmissions without full imaging capability, so the essential technology to use ELROI is available to any government or research organization. Essentially, ELROI's transmission technology is small, lightweight, cheap, self-powered, and otherwise self-sufficient, and its reception technology is available to anyone. For that reason, its creators believe it has what it takes to catch on and dramatically mitigate the space-traffic crisis.

> To actually track an ELROI-tagged satellite and read its ID would still require knowing the orbital details of the satellite in question: where and when to point the telescope. That information is always available to whoever controls the satellite and, in some cases, to an external agency with sufficient tracking capability, such as the Air Force. But even for the Air Force, satellite identification is not guaranteed and can

be absent whenever satellites fail to be registered immediately upon launch or, for example, when they cross paths in a confusing way. ELROI would nullify these problems going forward and, given the rapid over-proliferation of space objects, none too soon.

Still, there is a hint of irony in this manner of solution. There can be no question that developing a practical system capable of saving low earth orbit from becoming a hazardous wasteland is a tremendous multidisciplinary challenge for the modern age. And yet, paradoxically, at its core is single-photon detection the ability to perceive the absolute faintest possible blip of optical light—which, if you can read this, you might be able to do all by yourself. LDRD

—Craig Tyler

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